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Inter-Annual Variability of Net and Gross Ecosystem Carbon Fluxes: A Review

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Abstract

As the lifetime of regional flux networks approach twenty years, there is a growing number of papers that have published long term records (5 years or more) of net carbon fluxes between ecosystems and the atmosphere. Unanswered questions from this body of work are: 1) how variable are carbon fluxes on a year to year basis?; 2) what are the biophysical factors that may cause interannual variability and/or temporal trends in carbon fluxes?; and 3) how does the biophysical control on this carbon flux variability differ by climate and ecological spaces? To address these questions, we surveyed published data from 59 sites that reported on five or more years of continuous measurements, yielding 544 site-years of data.

We found that the standard deviation of the interannual variability in net ecosystem carbon exchange (162 gC m^{-2} y^{-1}) is large relative to its population mean (-200 gC m^{-2} y^{-1}). Broad-leaved evergreen forests and crops experienced the greatest absolute variability in interannual net carbon exchange (greater than +/- 300 gC m^{-2} y^{-1}) and boreal evergreen forests and maritime wetlands were among the least variable (less than +/- 40 gC m^{-2} y^{-1}).

A disproportionate fraction of the yearly variability in net ecosystem exchange was associated with biophysical factors that modulated ecosystem photosynthesis rather than ecosystem respiration. Yet, there was appreciable and statistically significant covariance between ecosystem photosynthesis and respiration. Consequently, biophysical conditions that conspired to increase ecosystem photosynthesis to from one year to the next were associated with an increase in ecosystem respiration, and vice versa; on average, the year to year change in respiration was 40% as large as the year to year change in photosynthesis. The analysis also identified sets of ecosystems that are on the verge of switching from being carbon sinks to carbon sources. These include sites in the Arctic tundra, the evergreen forests in the Pacific northwest and some grasslands, where year to year changes in respiration are outpacing those in photosynthesis.

While a select set of climatic and ecological factors (e.g. light, rainfall, temperature, phenology) played direct and indirect roles on this variability, their impact differed conditionally, as well as by climate and ecological spaces. For example, rainfall had both positive and negative effects. Deficient rainfall caused a physiological decline in photosynthesis in temperate and semi-arid regions. Too much rain, in the humid tropics, limited photosynthesis by limiting light. In peatlands and tundra, excess precipitation limited ecosystem respiration when it raised the water table to the surface. For deciduous forests, warmer temperatures lengthened the growing season, increasing photosynthesis, but this effect also increased soil respiration.

Finally, statistical analysis was performed to evaluate the detection limit of trends; we computed the confidence intervals of trends in multi-year carbon fluxes that need to be resolved to conclude whether the differences are to be attributed to randomness or biophysical forcings. Future studies and reports on interannual variations need to consider the role of the duration of the time series on random errors when quantifying potential trends and extreme events.

Introduction

Scientists have been making direct, quasi-continuous and long term eddy covariance measurements of net and gross carbon exchange between ecosystems and the atmosphere at solitary sites since the early 1990s (Black et al., 1996; Greco and Baldocchi, 1996; Saigusa et al., 2005a; Valentini et al., 1996; Wofsy et al., 1993). This set of early studies was influential because it gave the community confidence that eddy covariance measurements could be made on a quasi-continuous basis to produce annual budgets of carbon and water fluxes between ecosystems and the atmosphere. Starting in the late 1990s, a set of regional and global networks of eddy covariance flux measurements stations were formed, with the launching of the Euroflux, AmeriFlux, AsiaFlux and FLUXNET networks (Aubinet et al., 2000; Baldocchi et al., 2001; Yamamoto et al., 2005). Today, the sustained operation of many of these networks is providing us with many time series exceeding a decade in length, and some that are approaching twenty years in duration.

One of the overarching goals and aspirations of the flux networks was to collect time series long enough to assess the biophysical factors that may cause interannual variability and/or detect temporal trends in carbon fluxes. Until recently, too few of the time series from published eddy covariance study sites have been long enough to separate natural variability and emerging trends from sampling and measurement errors, as these sampling errors sum to the order of 20 to 50 gC m^{-2} y^{-1} (Elbers et al., 2011; Hollinger et al., 2004; Richardson et al., 2007).

There are many possible climatic, physiological and ecological reasons why ecosystem-atmosphere carbon fluxes may experience different degrees of interannual variability. To find the best and most pertinent explanations for carbon flux variability, it is important to examine the modulation of the gross flux components that are combined to form the net carbon flux. From first principles, we know that net ecosystem carbon exchange of an ecosystem (N_E) consists of three constituent fluxes--gross photosynthesis (assimilation), autotrophic (plant) respiration (R_a) and heterotrophic (microbial) (R_h) respiration.

Gross photosynthesis (G) of an ecosystem is sensitive to a different set of anomalous weather and climate variability than ecosystem respiration (Frank et al., 2015). Weather and climatic based explanations for year to year changes in carbon assimilation start with variability in clouds and precipitation and their impact on such primary drivers of assimilation, such as light, temperature, humidity deficits and soil moisture (Law et al., 2002; van Dijk et al., 2005; Yi et al., 2010). The combination of clouds, rain/drought, sunlight, and humidity can interact to either promote or retard photosynthesis. Wetter years will be associated with less sunlight, which may reduce photosynthesis, compared to a baseline (Zeri et al., 2014). And, drier years will be associated with more sunlight, which may increase photosynthesis up to a point; greater deficits in humidity and soil moisture will cause stomatal closure and reduce photosynthesis (Reichstein et al., 2007; Wolf et al., 2016). Photosynthesis responds to changes in temperature in a non-linear, quadratic fashion that is highly plastic (Baldocchi et al., 2001; Way and Yamori, 2014); some warming increases photosynthesis, too much warming is deleterious and the optimal temperature are known to acclimate with mean growing season temperature. Temperature can also influence ecosystem photosynthesis through phenology (Baldocchi et al., 2005; Richardson et al., 2010); the timing of phenological events is generally associated with temperature sums (Kramer et al., 2000). Timing of leaf out affects the length of the growing season, which in turn, can modulate seasonally-integrated photosynthesis (Gu et al., 2003). Plant and soil

respiration, on the other hand, tends to: 1) increase exponentially with temperature, given sufficient soil moisture (Atkin et al., 2005; Xu and Qi, 2001); 2) decline if soils are too dry or wet and 3) scale with carbon inputs into the rhizosphere from plant photosynthesis (Baldocchi, 2008).

In some regions, seasonal variations in climatic drivers, rather than variations in mean annual climate conditions, may be more important modulators in yearly summed carbon fluxes. For example, in cold regions the presence or absence of snow can have major impact on the amount of soil respiration during the winter (Monson et al., 2006a). In Mediterranean climate, the amount of rain during the spring growing season is more important than annual precipitation (Allard et al., 2008; Ma et al., 2007; Thomas et al., 2009); excess winter rain may run off and not contribute to the amount of water stored in the rhizosphere.

There can also be a disproportionate effect of 'hot moments' on the annual sums of net carbon fluxes. An analysis, using seven years of data from eight forested AmeriFlux sites, discovered that year to year differences in annual carbon fluxes were best described by the number of hours that short term fluxes exceeded a specified percentile (Zscheischler et al., 2016).

Year to year changes in the structural and functional traits of an ecosystem can also explain a significant portion of interannual variability in net and gross carbon fluxes (Richardson et al., 2007; van Dijk et al., 2005). For example, variations in leaf area index affect light capture and the surface area of the sources and sinks. With regards to functional traits, changes in the nitrogen supply will alter photosynthetic capacity and seasonally integrated photosynthesis (Reichstein et al., 2014). Changes in basal rates in soil and root respiration can occur through differences in leaf litter fall (Granier et al., 2008) and photosynthetic activity (Tang et al., 2005).

In the case of agriculture, management practices and cropping choices can be important factors that modulate gross and net carbon fluxes (Baker and Griffis, 2009; Dold et al., 2017; Knox et al., 2016; Suyker and Verma, 2010); the alternating choice of a C_4 (maize) vs C_3 (soybean) crop or decisions to irrigate or whether or not to till the soils affects annually integrated carbon fluxes on a year to year basis. For natural ecosystems, disturbance by fire, logging, insects and disease are other exogenous factors that can introduce year to year variations in net and gross carbon fluxes (Amiro et al., 2010; Clark et al., 2010; Dore et al., 2012; Frank et al., 2014).

Long term carbon flux measurements are needed to capture the rare extreme events that may have a detrimental or beneficial impact on an ecosystem (Frank et al., 2015). To capture information on the occurrence of rare droughts or variability in rain associated with *El Nino* and *La Nina* one may need 7 years of data, or more (Chen et al., 2009b; Wharton and Falk, 2016). Time since disturbance can also cause long term fluxes to differ on a year by year basis, as the greening of the landscape will cause photosynthesis to outpace respiration after x number of years (Amiro et al., 2010; Odum, 1969). Legacy effects can modulate year to year carbon fluxes, especially in wetlands and grasslands. For example, years with excessive vegetation will produce plenty of dead standing mass which will compete with live vegetation the next year for photons (Ma et al., 2016; Rocha et al., 2008). There also may be legacy effects following the return to normal conditions after an excessive drought if there is much plant, stem, shoot or root mortality.

Superimposed on the decadal record are trends in carbon dioxide and temperature, as the Earth experiences global change (Keenan et al., 2013; Schimel et al., 2015). Before we can detect whether or

not there are emerging trends in net ecosystem fluxes based on these chronic forcings we must understand the sources of natural variability and whether or not measurement uncertainty is greater or less than certain figures of merit. Finally, the duration of the time series must exceed a certain time threshold to be able to reduce measurement and sampling errors to an acceptable level and to be able to separate measurement and sampling errors from climatic and ecological sources of variation (Keenan et al., 2012).

Today, we are reaching a milestone where a large and diverse number of eddy covariance studies have been operating for more than a decade; more than 250 sites have been operating for 10 or more years (Chu et al., 2017; Pastorello et al., 2016). Subsequently, a growing and critical number of studies have been published in the peer review literature documenting the results from these long-term flux observations. Hence, we are at a juncture when this literature merits distillation and review. This review is intended to provide guidelines for future synthesis studies on interannual variability that are expected to be generated by the newest version of the FLUXNET database (Pastorello et al., 2016).

To perform this review, we harvested information from the suite of published carbon flux studies that report on long term measurements; they ranged between 5 and 18 years in duration. We divided the review into three sections. Part one is a panoramic view of interannual variability, which was conducted by examining the complied dataset as an ensemble. Here we address the following questions: how variable is net ecosystem carbon exchange (N_E) and its constituent components, gross ecosystem photosynthesis (G) and ecosystem respiration (R_e), on quasi-decadal time scales?; To what degree is interannual variability in net ecosystem carbon exchange imposed by modulation of ecosystem photosynthesis, and respiration, or by random noise and errors associated with the summation of hourly fluxes to annual time scales?; and do legacy or lag effect arise when looking at the lag autocorrelation functions of long time series? In part two, we examine lessons learned about interannual variability by dividing the database into major climate and ecological groups. In this section we address such questions as: which biophysical (weather vs ecological) forcings are most responsible to year to year variations in net and gross carbon fluxes?; do the controlling biophysical factors differ by climate and ecological space?; and where is year to year variability in N_E the greatest and least?. In part three, we draw upon the lessons learned and synthesize the findings. We ask if the published data records are long enough to detect trends given uncertainty in long term measurements? And, if so are temporal trends in carbon fluxes in a warmer world with more CO_2 detectable?

Methods and Data

Data used in this analysis are derived from an updated compilation of published data (Baldocchi, 2003; Baldocchi, 2008) that used the eddy covariance method to measure net ecosystem exchange (N_E). Negative values for net ecosystem exchange indicate a loss of carbon from the atmosphere, and a gain by the ecosystem. The interpretation of net ecosystem exchange was predicated on the inference of gross canopy photosynthesis (G) and ecosystem respiration (R_e) on annual time scales. Values of G and R_e were derived from conditional sampling of net carbon fluxes during day and night periods. For this analysis, we assigned positive signs for the values of G and R_e, so N_E equals R_e minus G. As we write this review, the literature database has 1781 site years of data published, recorded from more than 270 locations world-wide.

To produce daily and annually integrated carbon fluxes, missing values of the respective flux components were filled with data-derived, empirical algorithms (Reichstein et al., 2005). The most

prominent gap filling methods used by the scientific community include artificial neural networks, look-up tables or mean diel patterns (Falge et al., 2001; Moffat et al., 2007).

Because G and R_e are derived from N_E there has been some concern about errors from spurious correlation (Lasslop et al., 2010; Vickers et al., 2009). In a previous paper, we addressed this topic by testing the hypothesis that separate day/night and dormant/growing season sampling of carbon fluxes reduces spurious correlation when gross carbon fluxes are computed on annual time scales. Using data from a suite of FLUXNET field sites, we found that spurious correlations between derived gross carbon fluxes and net carbon exchange are generally small and most of the correlations between G and R_e at annual time scales were statistically true (Baldocchi et al., 2015). For background, we present the statistical distribution of annual sums of net and gross carbon fluxes in the database. Figure 1 shows the histogram of the published annual sums of net ecosystem exchange of carbon dioxide. This histogram indicates that ninety-five percent of the data resides between -748 and 482 gC m^{-2} y^{-1}. The mean of the distribution is -153 gC m^{-2} y^{-1} and its standard deviation is 289 gC m^{-2} y^{-1}.

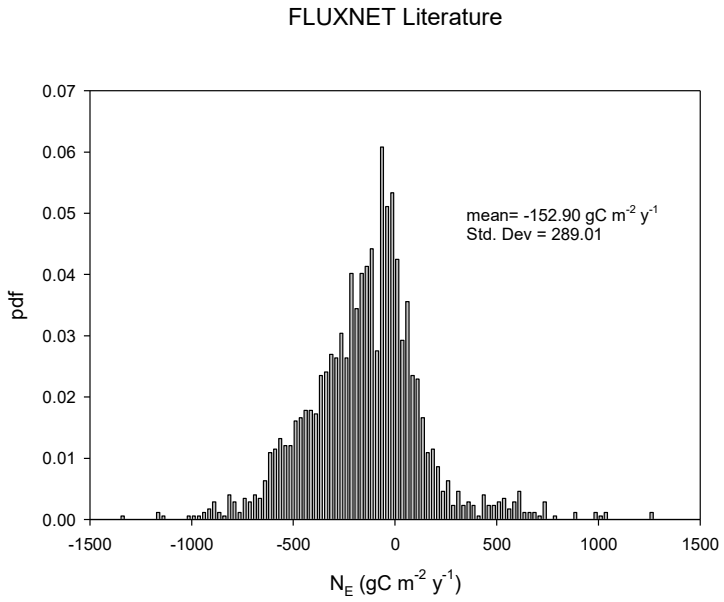


Figure 1 Histogram of published values of net ecosystem carbon exchange, N_E, derived from annual long studies using the eddy covariance method. The histogram is based on 1781 site years of data. The y axis represents the probability density function, pdf.

Histograms for data associated with gross ecosystem photosynthesis (G) and ecosystem respiration (R_e) are shown in Figure 2. Figure 2a shows that ninety-five percent of the data for G reside between 176 and 2919 gC m^{-2} y^{-1} and that the histogram possesses a mean equal to 1294 gC m^{-2} y^{-1} and a standard deviation equal to 684 gC m^{-2} y^{-1}. Figure 2b shows that ninety-five percent of the data for R_e are confined between 219 and 2511 gC m^{-2} y^{-1}. This distribution possesses a mean of 1117 gC m^{-2} y^{-1} and a standard deviation of 578 gC m^{-2} y^{-1}. With the majority of flux sites in the temperate zone, these histograms tend to have long tails, and are biased from an under representation of measurements in the tropics which have larger values of G and R_e (Beer et al., 2010).

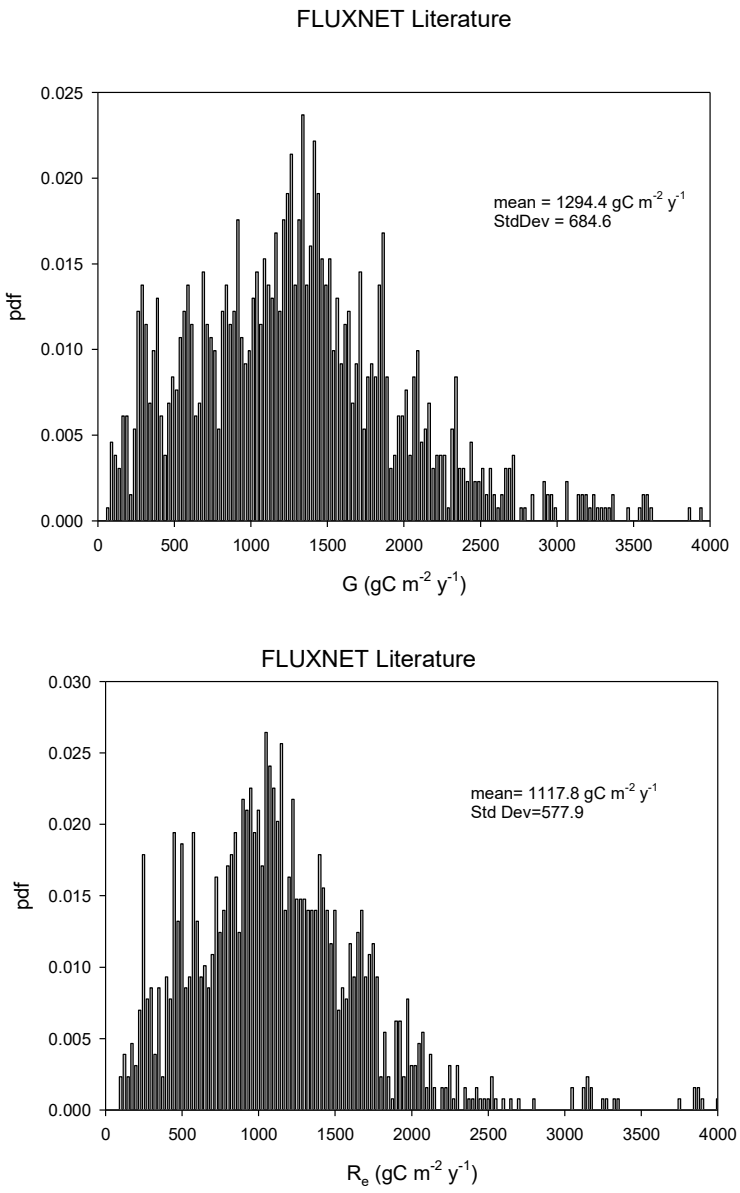


Figure 2 a) Histograms of published values of ecosystem photosynthesis (G) at annual time scales, reported in the literature; b) histogram of published values of ecosystem respiration (R_e) at annual time scales, reported in the literature. These gross carbon fluxes were derived from eddy covariance measurements of net ecosystem carbon exchange. The y axes represent the probability density function, pdf.

For this analysis, we drew on data from 59 study sites that reported 5 or more years of flux data, yielding 544 site years of data (Table 1). This dataset comprised of 5 studies with 15 or more years reported; the longest published study has 18 years of observations (Froelich et al., 2015). We also analyzed 18 studies with ten to 15 years of data and 36 studies with 5 to 10 years of data. The cut-off at 5 years may be viewed as arbitrary, but given that the majority of relatively long term studies are of this duration it is worth including these studies for the sake of this review. Later in the paper we will address

the question 'how long is long enough?', with regards of the detection limit of year to year variations in annual carbon fluxes from random noise.

Panoramic View of Interannual Variability

The first query of the long-term database is: how variable are net and gross carbon fluxes on a year to year basis? If variability is low, we may have ample information to describe the carbon balance of these ecosystems. But, if interannual variability is great, we may need longer datasets to capture and explain the sources of this temporal variation.

We inspected the anomalies from the annual mean of each of the 59 time-series and plotted the histogram. For net ecosystem carbon exchange, the histogram was non-Gaussian (Figure 3); its distribution was peaked and positively skewed. The statistics for this distribution of anomalies possessed a standard deviation equal to 162 gC m^{-2} y^{-1}, a skewness equal to 0.833 and a kurtosis equal to 12.5. Ninety-five percent of the data were bound between -317 and 328 gC m^{-2} y^{-1}. Given the population mean of N_e around -200 gC m^{-2} y^{-1} (Figure 1), we conclude that the interannual variability of net ecosystem carbon exchange is very large. The high variability of net carbon fluxes has implications the uncertainty bounds of data used to benchmark carbon cycle models and on setting the probability distribution of priors used for Bayesian models (Zobitz et al., 2011).

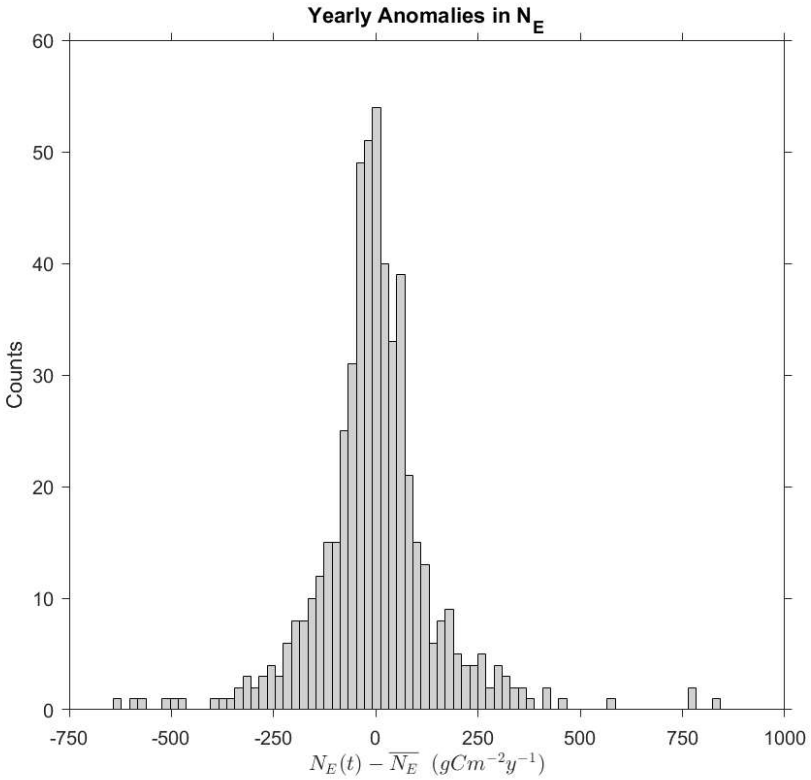
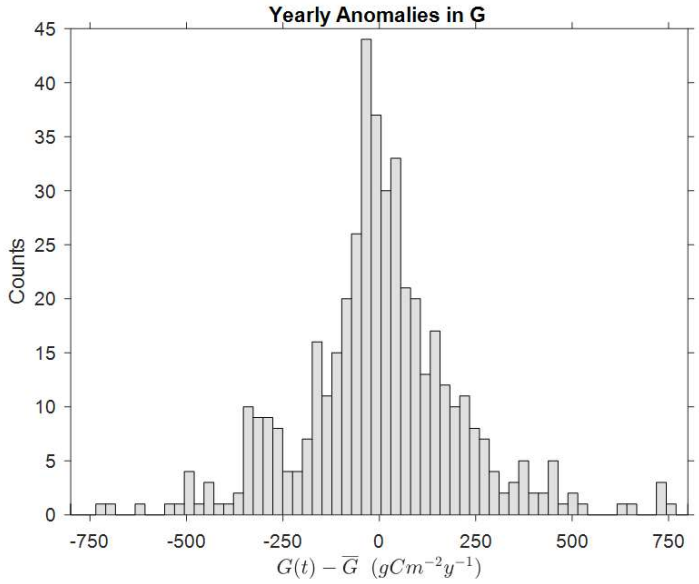


Figure 3 Histogram of yearly anomalies in net ecosystem carbon exchange from the literature data pool of 544 site years of data. Anomalies were computed with regards to the annual mean of each time series in the database.

Variations in N_E can be due to large excursions in G or R_e or some combination of the two. In Figure 4a we examine the histogram of yearly anomalies in mean annual fluxes of gross photosynthesis. The standard deviation of interannual anomalies in G was 230 gC m^{-2} y^{-1}, which was equivalent to 17.8% of population mean of G (Figure 2a). The skewness was -0.326, and its kurtosis was 8.51. Ninety-five percent of the interannual anomalies in the histogram for anomalies in G ranged between -475 and 468 gC m^{-2} y^{-1}. In comparison, 95% of the anomalies in R_e, showed in Figure 4b, ranged between -243 and 308 gC m^{-2} y^{-1}. This distribution possessed a standard deviation of 137 gC m^{-2} y^{-1}, which was equivalent to 12.6% of population mean of R_e (Figure 2b). The skewness was 0.472, and its kurtosis was 5.75.



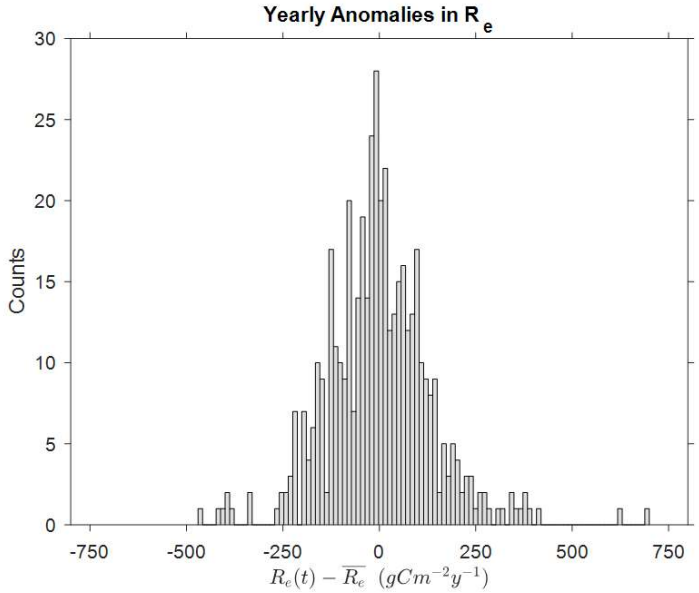


Figure 4 Histogram of yearly anomalies in a) gross primary production, or photosynthesis (G) and b) ecosystem respiration, R_e. These data are derived literature data pool of 454 site years of data. Anomalies were computed with regards to the mean of each time series in the database.

The next question we explore are the degrees that the variances of inter-annual variations in N_E are associated with variances in G or R_e? We can define the variance in net ecosystem exchange (N_E) as the sum of the variance in gross canopy photosynthesis (G) and ecosystem respiration (R_e), minus two times the covariance between G and R_e (Lasslop et al., 2010):

$$\sigma^2_{N_E} = \sigma^2_G + \sigma^2_{R_e} - 2\mathrm{cov}(G, R_e) \quad (1$$

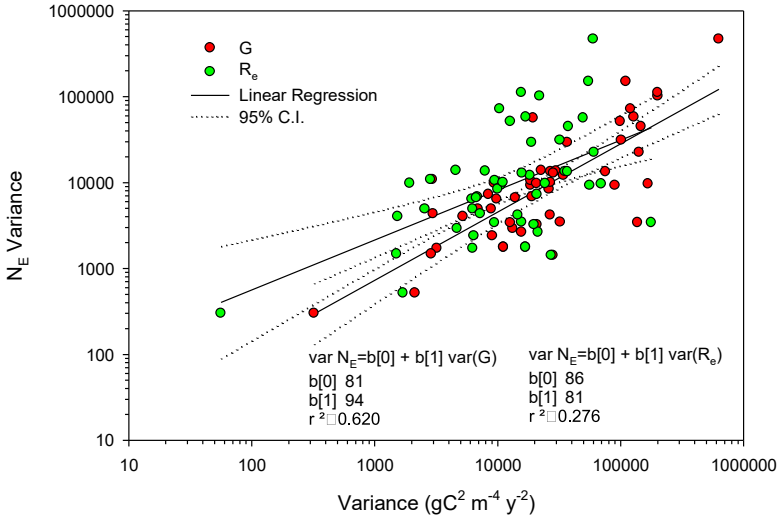
In addition, one can express the covariance between G and R_e as a product of the respective standard deviations and the correlation coefficient (r_{GRe})

$$\mathrm{cov}(G, R_e) = \overline{G' R_e'} = r_{G R_e}\, \sigma_G\, \sigma_{R_e} \quad (2$$

The interpretation of the sources of variance in N_E can be complicated by how the constituent terms add, covary and subtract with one another.

Normalizing the population of the mean of the constituent variances in Equation 1 we find that the variance in G is about twice the variance of N_E and that the variance in R_e is about 76% of the variance of N_E; $\frac{\sigma^2_G}{\sigma^2_{N_E}}$ equaled 2.038 and $\frac{\sigma^2_{R_e}}{\sigma^2_{N_E}}$ equaled 0.767. The covariance between G and Re interact to reduce the variance in N_E by about 176%; the term, $\frac{-2\, r_{GR_e} \sigma_G \sigma_{R_E}}{\sigma^2_{N_E}}$, equaled -1.763. From these ratios one can conclude that the direct contribution of the variance in G on the variance in N_E was about 2.65 times greater than the impact of the variance in R_e.

We dive deeper into the database by examining the relationship between the variances in N_E, computed for each site, and the terms in Equation 1 (Figure 5). The slope of the linear regression between the variances of G and N_E (0.794) was greater than the slope between the variances of R_e and N_E (0.58). Moreover, a lower portion of the variance in N_E was explained by the variance in R_e (r^2 = 0.276) than by the variance in G (r^2 = 0.620). While we conclude that a greater fraction of the variance in N_E is explained by the variance in G than the variance in R_e, it is clear that the magnitude of the variance of N_E was conditional on the values of the variances of G and R_e. For example, when the variance in N_E was relatively low (e.g. 1000 $gC^2\ m^{-4}\ y^{-2}$) the variance in G equaled 1487 $gC^2\ m^{-4}\ y^{-2}$ and the variance in R_e equaled 271 $gC^2\ m^{-4}\ y^{-2}$. When the variance in N_E was at the midpoint of the data population (27,844 $gC^2\ m^{-4}\ y^{-2}$), the variance in G was 98,198 $gC^2\ m^{-4}\ y^{-2}$ and the variance in R_e was 83,246 $gC^2\ m^{-4}\ y^{-2}$. Finally, variance in N_E equaled 38,125 $gC^2\ m^{-4}\ y^{-2}$ when these variance terms were identical (145,989 $gC^2\ m^{-4}\ y^{-2}$).



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295 Figure 5 The regression between the variance in net ecosystem exchange (N_E) and gross photosynthesis
296 (G) and ecosystem respiration (R_e). Regression coefficients are for the log transform of log(y)=b(0) + b(1)
297 log(x).

298 The degree with which anomalies in G and R_e covary with one another, as expressed in Equation 2, is
299 inspected in Figure 6. If the correlation between G and R_e is small, then the third term on the right-
300 hand side of Equation 1 may be small. Conversely, if the correlation between G and R_e is great, this third
301 term can offset sources of variance with the individual terms. Anomalies in R_e are about 42% as large as
302 anomalies in G. Moreover, there was a larger than expected degree of decoupling between anomalies
303 in G and R_e, as the coefficient of determination (r^2) indicates that only 49% of the variation in R_e are
304 explained by G.

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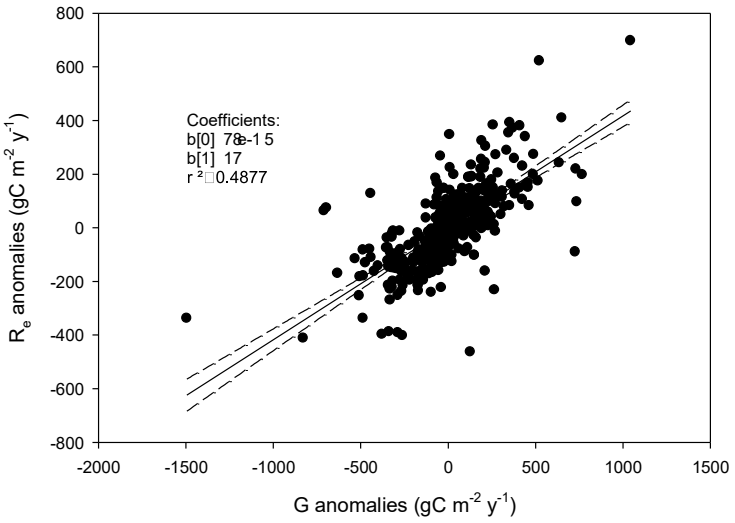

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307 Figure 6 Examination of the covariance between ecosystem photosynthesis (G) and respiration (R_e).
308 Plotted here are the yearly anomalies with the long term means of the data.

309 With longer datasets, we can inspect the degree of year to year coupling between G and R_e that spans a
310 spectrum of climates and ecosystem types (Figure 7), dG/dt and dR_E/dt. We observe a positive slope
311 between year to year changes in G and R_e, which is consistent with an earlier report using a smaller data
312 set consisting of shorter time series (Baldocchi, 2008). In sum, conditions that will cause G to increase
313 from year 1 to year 2 will be accompanied by a proportional, but smaller (49%), increase in R_e.
314 Conversely, conditions that lead G to decrease from year 1 to year 2 will be associated with a
315 compensating decrease in R_e. Hence, interannual variations in N_E have the potential to be more
316 sensitive to climate and weather anomalies that drive photosynthesis than respiration. This is a key
317 lesson in searching for attributions causing variations in N_E under extreme climate events.

318

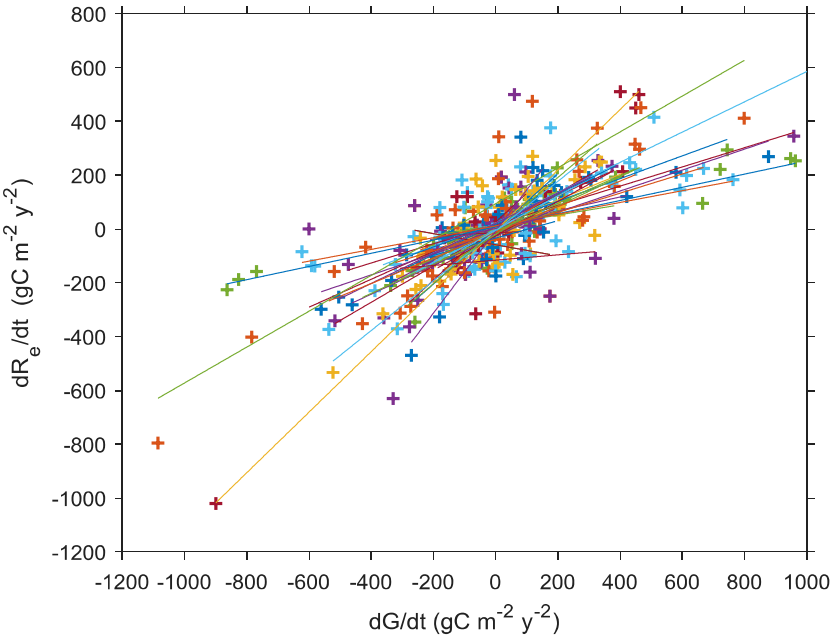


Figure 7 Relation between year to year changes in gross ecosystem photosynthesis (dG/dt) vs ecosystem respiration (dR_e/dt). The slope of the population is 0.494, the intercept is -1.137 and r^2 equals 0.552, N = 398. Color codes indicate data points from each study.

Contained within Figure 7 are four sets of data where year to year changes in R_e were equal or greater than year to year changes in G. The evergreen conifer forests in the Pacific northwest (Wind River, Campbell River), a deciduous beech forest in Denmark, and a grassland in North Carolina, which was in the initial stage of post agricultural succession, fell into this category. Also noteworthy were data from two other grasslands that had slopes close to one. These included a grassland in California and a sphagnum, grass bog in Scotland. Signals emerging from these data suggest that sites associated with two functional types (evergreen, humid conifer forests and grasslands) may be more vulnerable to switching from being carbon sources to sinks with further perturbations in carbon fluxes from factors like climatic and environmental change.

With regards to weather and climate, we know there is some degree of persistence in the system; there is a high likelihood that today's weather will be the same tomorrow, and next year (Rybski et al., 2006). The next question we ask is to what degree is there persistence in net carbon fluxes, from one year to the next. We can investigate this by calculating and plotting the lag autocorrelation coefficients for each of the detrended time series (Figure 8).

We see several types of behavior. Overall, it took between one-half to five years for the lagged autocorrelation coefficients to cross zero. Of this population, we found one set of sites that became negatively (< -0.5) correlated with itself after a one-year lag; these correlation coefficients are significantly different than zero, as determined from the 95% confidence interval of a random time series. The implication of these negative lag correlation coefficients indicates a highly oscillatory behavior in the net carbon fluxes from year to year. Sites in this category included an alpine meadow, a sub-tropical forest, evergreen oak woodlands, a grassland, temperate evergreen forests and a deciduous forest. The third feature in Figure 8 relates to decadal time scales. We found that the lag correlations

were generally not significantly different from zero, as detected by the band of the 95% confidence interval that was produced by a random time series. So, at this time we are unable to detect any world-wide variability in carbon fluxes that are at the time scales of El Nino's and La Nina's. Only one case experienced a relatively strong negative autocorrelation at the time scale of a decade; this occurrence was from the 18 year long record at the deciduous forest in Ontario, Canada. Its ten-year lag autocorrelation equaled -0.28, which was just inside the associated value of the 95% confidence interval (-0.29).

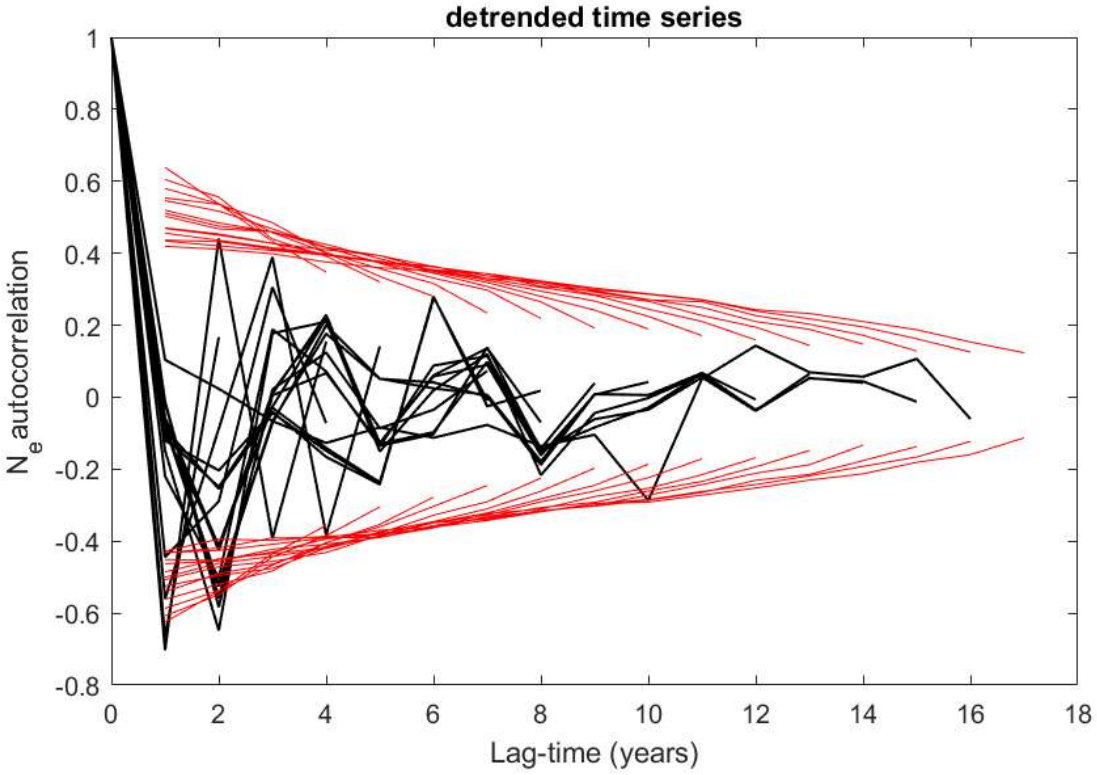


Figure 8 Lagged auto-correlation function for net ecosystem exchange at the 59 sites listed in Table 1. Each line denotes results from time series of one site study. To detect if the lag correlation values were significantly different from zero we performed a set of auto-correlation computations on a set of random numbers of progressive lengths (5 to 18). From these computations, we computed the 95% confidence intervals of lag correlations from an repeated ensemble (5000) of calculations, as shown with the red lines.

Lessons Learned from Ecological and Climate Regions

In this section, we divide the database into the dominant ecological and climatic regions of the world. We then distill which set of climate/ecological forcings and circumstances are responsible for driving carbon flux interannual variability in these regions. We also inspect the data to determine if any trends in carbon fluxes are being detected in our changing world? One of the lessons to emerge from the following analysis will be that there are a variety of explanations for interannual variability of carbon fluxes, and they differ region by region.

Boreal Evergreen Forests

Boreal evergreen forests thrive in the circumpolar latitude belt between 50 and 70 degrees of North America, Scandinavia, and Asia. They comprise of trees on the order of 10 m tall and establish canopies that possess a leaf area index on the order of 3 to 4 m^2 m^{-2} (Bonan and Shugart, 1989; Luyssaert et al., 2007).

Across the boreal forest, the interannual standard deviation of net carbon fluxes was relatively modest, less than 50 gC m^{-2} y^{-1} (Dunn et al., 2007; Ilvesniemi et al., 2009; Richardson et al., 2007; Soloway et al., 2017; Ueyama et al., 2014), compared to data from many other climate and ecological spaces shown in Figure 5 and Table 1.

In Finland, links between climate and year to year variability in net and gross carbon fluxes were not clear and only explained a small fraction of the variability in annual net ecosystem exchange (Ilvesniemi et al., 2009). However, the start of the growing season was best associated with air temperature and the end of the growing season was best described by day length (Suni et al., 2003). In contrast, an analysis of 15 years of data from a boreal deciduous and an evergreen forest in Saskatchewan and Manitoba, Canada, respectively, revealed that interannual variability in net carbon exchange was best explained by the interval of the dates in autumn when net carbon uptake and gross ecosystem photosynthesis ceased, a period called the 'autumn interval' (Wu et al., 2012). At these Canadian sites, there was no significant relationship between net carbon uptake and the spring interval between when ecosystem photosynthesis and net carbon uptake commenced. Another analysis of data from the mature (160 year-old) black spruce forest, in Manitoba, Canada, revealed the net ecosystem carbon exchange switched back and forth from being a carbon source or sink (Dunn et al., 2007; Soloway et al., 2017). In general, year to year variations in net carbon exchange were attributed to variations in air temperature, soil moisture, water balance and summer solar radiation. More specifically, warming and thawing of the soil caused ecosystem respiration to lag ecosystem photosynthesis. In these wet and cold boreal ecosystems, a shallow water table would suppress respiration and favor photosynthesis, causing the system to be a small carbon sink. Converse conditions would cause the ecosystem to be a carbon source.

For a boreal spruce forest growing in Alaska, interannual variation in net carbon exchange was forced mainly by changes in ecosystem respiration, which was being pushed by autumnal warming (Ueyama et al., 2014). At the southern fringe of the boreal zone, in Maine, United States, 40% of the variance in net ecosystem exchange was due to environmental drivers and 55% was due to biotic factors (Richardson et al., 2007).

Disturbance also plays a role in interannual variation of carbon fluxes in the boreal region (Amiro et al., 2010; Goulden et al., 2011). Following recovery from logging, a boreal forest in Canada will continue to be a carbon source for 10 years. Afterwards, it becomes carbon neutral and later a carbon sink (Coursolle et al., 2012).

None of these long-term studies identified the presence or absence of winter snow as a modulating factor, explicitly. However, Monson et al. (2006b) reported that winter respiration of an alpine forest, which is an elevated version of a boreal forest, depends upon the state of the snow pack. Soil temperatures are colder when the snow pack is shallow, which reduces soil respiration. And, a recent

regional analysis inferred that a decrease in winter respiration from declining snow pack explains an enhancement in the carbon sink of northern forests (Yu et al., 2016).

Temperate Evergreen Forests

Temperate evergreen forests span a wide range of climate and soil conditions and are often intensively managed (Jarvis and Leverenz, 1983). On average, temperate evergreen forests maintain closed canopies with high leaf area indices (7 +/- 3 m^2 m^{-2}), tall trees (20 +/- 12 m) and large amounts of standing biomass (14,934 +/- 13,562 gC m^{-2})(Luyssaert et al., 2007). Temperate evergreen forests living in the humid Pacific northwest of North America possess some of the greatest biomass, highest leaf area index and the longest living trees. Conifer forests in the southern United States and Europe are intensively managed and logged at specific time intervals. Hence, long term carbon fluxes often include additional variability due to disturbance (Bracho et al., 2012; Dore et al., 2012). In addition, evergreen forests, with longer growing seasons, tend to grow on poorer soils, compared to deciduous forests.

There exist two sets of long term carbon flux studies in the wet humid, temperate zone of western North America (Krishnan et al., 2009; Wharton and Falk, 2016). One nine year study in British Columbia over a relatively young (58 year old) Douglas fir (*Pseudotsuga menziesii*) forest concluded that the major drivers of interannual variability of annual carbon fluxes were annual and spring air temperatures and water deficits during the late summer and autumn (Chen et al., 2009b; Krishnan et al., 2009). This forest was a strong net carbon sink (-356 +/- 51 gC m^{-2} y^{-1}). The other study presented 13 years of data from an old age Douglas fir forest (Wharton and Falk, 2016). The net carbon budget was near zero, -32 +/- 84 gC m^{-2} y^{-1}. The interannual variability of net ecosystem exchange of the old Douglas fir forest growing in Washington was 64% greater than that of the younger forest growing in British Columbia. With this comparison, we start to see evidence for the effect of stand age on interannual variability of carbon fluxes of these temperate rain forests.

While the Pacific northwest is wet and receives ample rainfall, it experiences relatively dry summer growing seasons (Lassoie et al., 1985). Hence, year to year differences in net carbon exchange are strongly affected by spring temperature and late summer water deficits (Chen et al., 2009b; Krishnan et al., 2009). On a seasonal basis, light explained 85% of the variability in monthly ecosystem photosynthesis and temperature explained 91% of the variation in monthly ecosystem respiration. In sum, net carbon exchange was highest when precipitation was normal and air temperature was 'optimally' warm and lowest during the warmest and driest years. Variability of net and gross carbon fluxes in this region are closely linked to the El Nino-Southern Oscillation (ENSO), and the Pacific North American (PNA) and Pacific Decadal Oscillations; the old-age forest was a stronger sink during the favorable climate conditions of La Nina and was either a source or near neutral during El Nino years (Wharton and Falk, 2016).

Ponderosa pine (*Pinus ponderosa*) thrive in semi-arid mountain regions from east side of the Cascade mountains in Oregon, through the Sierra Nevada mountains of California and Nevada and into northern Arizona. The carbon budget of these forests is often disturbed by fire and logging. Two sets of studies have produced long term records on net and gross carbon exchange of these forests (Dore et al., 2010; Thomas et al., 2009). In both instances year to year variations in net ecosystem exchange, as quantified by the standard deviation, were on the order of 100 gC m^{-2} y^{-1}, indicating a highly variable ecosystem.

For a 90 years old ponderosa pine stand in Oregon, mean net ecosystem carbon exchange was -464 +/- 116 gC m^{-2} y^{-1} over seven years. Interannual variation in growing season length of the hydro-ecological year could be as large as 45 days (Thomas et al., 2009). However available soil water was the main factor modulating net and gross carbon fluxes on a year to year basis. This team concludes that variability in annual ecosystem photosynthesis, which is modulated by available soil water, drives the interannual variability in net ecosystem carbon exchange. In Arizona, disturbance by fire and thinning were factors driving interannual variability in net and gross carbon fluxes of another ponderosa pine forest (Dore et al., 2012).

Slash pine (*Pinus elliotii*) forests in Florida experience relatively frequent logging cycles (20 to 25 years). An 11 year study across the disturbance and recovery time history was the most variable in the record (111 +/- 683 gC m^{-2} y^{-1}) in this database. The forest lost between 800 and 1250 gC m^{-2} y^{-1} during the first 3 years after disturbance, was carbon neutral after 5 years and was a strong sink (-400 to -700 gC m^{-2} y^{-1}), there after (Bracho et al., 2012). Aggrading leaf area index was a dominant factor driving this forest from a large carbon source to sink. Across the data base that was inspected this site possessed the greatest year to year variability in N_E. In comparison, the mid-rotation stand had a negative NEE value of -669 +/- 98 gC m^{-2} y^{-1} over 9 years.

For forests growing in Europe, we find that a 100 years old spruce forest (*Picea abies*) in Germany is one of the more productive of those surveyed, but its net ecosystem carbon exchange is highly variable; its mean net ecosystem exchange over 10 years was -550 +/- 91 gC m^{-2} y^{-1}) (Grunwald and Bernhofer, 2007). High variation in net and gross carbon fluxes was attributed to a wide span of rainfall (500 to 1000 mm y^{-1}) and mean annual air temperature (6 to 9 C) during the duration of the time series at this continental site. Carbon update was greatest during the warm and relatively wet years and least during the warm and driest years. The wettest year depressed net carbon uptake, which is expected due to light limitations by clouds.

Temperate Deciduous Forests

The geographic band for temperate deciduous forests range between 30 and 50 degrees across North America, Europe and Asia (Barnes, 1991; Hicks and Chabot, 1985). These forests rely on a substantial, but not excessive amount of rainfall (800 to 1400 mm per year), survive cold winters down to about -20 C and can withstand warm summer temperatures up to the low 30s (Baldocchi and Xu, 2005). These forest tend to be tall (19 +/- 7 m) and possess a closed canopy with high leaf area index (6 +/- 3 m^2 m^{-2}) (Luyssaert et al., 2007).

Temperate deciduous forests are one of the ecosystems with the largest number of long term eddy covariance, carbon flux measurement studies (Froelich et al., 2015; Granier et al., 2008; Herbst et al., 2015; Novick et al., 2015; Pilegaard et al., 2011; Saigusa et al., 2005b; Shao et al., 2014; Sulman et al., 2016; Urbanski et al., 2007; Wilkinson et al., 2012; Wilson and Baldocchi, 2001). Interannual variation of N_E among this climate and functional type is relatively large. On average, the standard deviation of interannual N_E of these datasets is close to +/-100 gC m^{-2} y^{-1} (Table 1).

The longest published time series of N_E comes from the mixed forest near Borden, Ontario, Canada, and is 18 years long (Froelich et al., 2015). At this site, the mean N_E was -177 +/- 115 gC m^{-2} y^{-1}. The authors reported that light and temperature were the main meteorological factors forcing interannual variation in carbon fluxes. Net carbon exchange also correlated well with length of growing season, which ranged

between 111 and 164 days per year. At this site a small trend in N_E was reported (15 gC m^{-2} y^{-2}) and was attributed to slow long term warming (0.09 C y^{-1}).

Harvard Forest, in Massachusetts, USA, was the first locale at which the first long term carbon fluxes were measured (Wofsy et al., 1993), and is the source of the longest measured time series. This team's analysis of 13 years of measurements found that uptake rates doubled as the forest aged from 75 to 110 years (Urbanski et al., 2007); they concluded that tree biomass, successional changes in forest composition and disturbance were dominant factors driving interannual and decadal variations in net carbon exchange. Length of the growing season and deepness of winter snow has also been identified as a factor affecting net carbon exchange at this site (Goulden et al., 1996).

Three long term studies come from beech forests growing across Europe and differing in age (Granier et al., 2008; Herbst et al., 2015; Pilegaard et al., 2011). Each experienced different sources of variation. Over an 80 to 90 year old beech forest in Denmark, a trend N_E measured was detected; it increased 23 gC m^{-2} y^{-2} as the length of the growing season increased 1.9 days per year across a 13 year period (Pilegaard et al., 2011). In comparison, a 40 year old beech forest in France experienced high variability in N_E due to length of the growing season and the duration of soil water deficits (Granier et al., 2008). This forest was thinned, but this thinning did not change photosynthesis markedly and year to year changes in ecosystem respiration were not linked to climate forcings. In Germany, an unmanaged beech forest with trees up to 250 years old was compared with a managed beech forest with trees averaging 130 years old (Herbst et al., 2015). Average net carbon exchange of the two forests did not differ. However, this team found that interannual variability of N_E was greater for the managed, than the unmanaged, forest (119 vs 70 gC m^{-2} y^{-1}). The lowest years of carbon uptake occurred when fruit production was greatest. In addition, the old age, unmanaged forest suffered more from the 2003 drought/heat spell and no trend in N_E was detected, in contrast to the beech forest in Denmark.

An 80 year old deciduous forest in the United Kingdom was highly productive (-486 gC m^{-2} y^{-1}) and experienced moderate (+/-73 gC m^{-2} y^{-1}) variability over 12 years (Wilkinson et al., 2012).
At this site year to year differences in the growing season was small and stable (165 +/- 6 days).
Interannual variations in sunlight modulated carbon fluxes at this site most (variations in radiation accounted for 46% of the variation in N_E). Insect infestations were another source of variation. This is a natural and possible source of variation in carbon fluxes that would be missed with shorter term studies.

In Japan, interannual variability in net carbon exchange of a temperate deciduous forest was strongly associated with spring air temperature and the timing of leaf out (Saigusa et al., 2005a); it was also reported that the occurrence of *El Nino* favored earlier leaf emergence. On the other hand, the effect of the monsoon on clouds and summer solar radiation did not have a discernable effect on interannual variation in net carbon exchange.

In sum, length of growing season is a dominant factor affecting N_E across much of the deciduous forest biome. Deciduous forests tend to optimize the length of growing season by leafing out when soil temperature matches mean annual air temperature (Baldocchi et al., 2005). If the plants leaf out too early they are susceptible to damage by late freeze or frost events (Gu et al., 2008). In contrast, if they are too conservative and leaf out too late they have a shorter period to accumulate carbon.

Evergreen Broadleaved Forests

Evergreen broadleaved forests thrive where there is no frost or freezing (Woodward, 1987). Examples include the tropical forests of South America, Africa and Asia, subtropical forests, like the eucalyptus forests of Australia, and the evergreen oaks of zones with Mediterranean type climates.

Temperature is mostly invariant in the tropics. So year to year differences in rainfall and sunlight tend to have the greatest impact on interannual carbon fluxes (Araújo, 2002; Goulden et al., 2004; Wu et al., 2016; Yan et al., 2013; Zeri et al., 2014). Often tropical forests are light limited due to the presence of clouds and frequent rain, so there can be an unexpected consequence with mild drought, more light and photosynthesis.

Six years of carbon flux observations from a southwestern Amazonian forest encountered two years of severe drought and one year of flooding (Zeri et al., 2014). At this site, carbon fluxes tend to be highest at the end of the dry season when sunlight is ample and diffuse light increases light use efficiency. This site is noteworthy for the observation of a lack of synchrony between monthly rainfall and carbon uptake. Consequently, legacy effects of the 2005 drought were noted the year after; this year the forest was a carbon source even though gross photosynthesis remained relatively high (2000 gC m^{-2} y^{-1}).

In another part of the Amazon, near Santarem, Brazil, it was found that hourly variations in solar radiation, diffuse light fraction and vapor pressure deficits could account for 75% of the variability in ecosystem photosynthesis (Wu et al., 2016). When carbon fluxes were aggregated into daily, monthly and annual integrals, these variables explained a progressively smaller fraction of variability in photosynthesis (down to 3%). Instead, biological factors, such as light use efficiency and phenology, had a larger (63%) explanatory power.

Across Asia, tropical forests assimilate carbon at greater rates and with greater interannual variability (-397 +/- 94 gC m^{-2} y^{-1}) than sub-tropical forests (-166 +/- 49 gC m^{-2} y^{-1}) (Yan et al., 2013). Rainfall is the fundamental driver of carbon exchange of tropical and sub-tropical forests and best explained interannual variability in N_E. The sub-tropical forest was a carbon sink during wet and dry seasons. In contrast, the tropical forest was a carbon source during the wet season, when ecosystem respiration outpaced carbon assimilation. Drought reduced wet season respiration, enabling the tropical forest to be a stronger carbon sink during the dry years.

Two papers reported on measurements from eucalypt forests, a natural stand in Australia (van Gorsel et al., 2013) and a plantation in Portugal (Rodrigues et al., 2011). Ten years of carbon flux measurements over a native eucalypt stand revealed that extended clouds during wet periods and extended dry periods both reduced carbon uptake (van Gorsel et al., 2013). Drought also promoted an insect attack, which caused the forest to become a carbon source. Large year to year variations in rainfall (between 370 and 750 mm y^{-1}) at a Portuguese eucalypt plantation caused this stand to switch back and forth from being a strong sink (-865 gC m^{-2} y^{-1}) to being carbon neutral (-11 gC m^{-2} y^{-1}) (Rodrigues et al., 2011).

As has been shown with shorter time series, evergreen broad-leaved forests in semi-arid regions, like Australia, or Mediterranean climates, like France, Italy and Portugal can experience variability by the amount of rain during the wet growing season (Allard et al., 2008; Pereira et al., 2007). And, drought stress reduces ecosystem photosynthesis more than respiration.

Grasslands

Grasslands are associated intermediate rainfall conditions that are too dry to sustain forests and too wet for deserts (Woodward, 1987). While grasslands thrive across wide swaths of North and South America and Eurasia, long term published data come only from the Mediterranean climate of California and the benign maritime climates of the British Isles.

Based on 15 years of data, an annual grassland in California, with a winter and spring growing season experienced reduced photosynthesis during the wettest years (Ma et al., 2016). This system also experienced legacy effects on ecosystem respiration. Consider a year with high biomass production. A large fraction of this biomass will persist and be present the next growing season. This dead biomass will compete for photons with emerging sprouts and reduce their carbon assimilation.

Grass grows nearly year-round in Ireland. Management, in terms of grazing and harvesting, were among the more dominant factors affecting carbon fluxes in this maritime climate where environmental conditions were often not limiting (Peichl et al., 2012).

Semi-Arid Savanna

Semi-arid ecosystems can be viewed as natural models for a future world that is drier and warmer, as these system experience much year to year variability in rainfall (30 to 40% coefficient of variation), compared to more humid and mesic climate zones (Fatichi et al., 2012). Semi-arid savannas tend to be about 12 +/- 8 m tall and support an open canopy (leaf area index equals 3.5 +/- 1.2) (Luyssaert et al., 2007; Sankaran et al., 2005).

Savanna woodlands in regions with Mediterranean climates, cool, wet winters and hot dry summers, year to year variations are mostly driven by the amount of rain during the spring (Allard et al., 2008; Ma et al., 2016; Ma et al., 2007). Both G and R_{eco} increased linearly with increasing spring rainfall up to a limit. Years with excessive rainfall, meet the water demand of the open woodlands and end up limiting G through cloudiness and limited light. Carbon uptake is limited by physiological soil water deficits during the dry hot summers, so small absolute changes in rainfall may have large relative.

Wetlands/Peatlands/Tundra

Two long term flux studies over wetlands were conducted on the British Isles, Scotland and Ireland (Helfter et al., 2015; McVeigh et al., 2014). Both studies reported very small annual fluxes (-64 gC m^{-2} y^{-1} in Scotland and -55 gC m^{-2} y^{-1} in Ireland). Moreover, the clement, maritime climate of these locales produced time series that ranked among the least variable (the standard deviations in N_E were less than 38 gC m^{-2} y^{-1}).

Despite the small range, interannual variability in N_E depended upon the length of growing season and depth of the water table. These ecosystems experienced an anti-correlation between R_e and G, when drought increased R_e, by decreasing the water table, and decreased G (Helfter et al., 2015). Conversely, warmer winter temperatures lead to an earlier spring, longer growing season and greater G. Based on these studies, anticipated trends in declining water tables with global warming are anticipated to cause these ecosystems to become smaller carbon sinks and potentially carbon sources.

The first set of long term carbon flux data were published recently from two representative Arctic ecosystems in Alaska, a wet sedge and heath tundra (Euskirchen et al., 2016). These ecosystems are

606 shifting from being a small carbon sink to losing carbon, as increasing air and thawing soil temperatures
607 are triggering the decomposition of stored organic matter that had been inactive in frozen layer. Later
608 dates of autumnal freezing are also extending the period of net carbon loss.

609 *Crops*

610 Management has an overwhelming impact on interannual variability of crops, depending upon the
611 choice of crop (corn or soybeans) and whether it is rainfed or irrigated (Knox et al., 2016; Suyker and
612 Verma, 2012). With maize/soybean rotation, both irrigated and rainfed maize are a moderate carbon
613 sink, compared to soybean, which ranges from being carbon neutral to a small carbon source (Suyker
614 and Verma, 2012). Yet, given a specific crop, exogenous factors, like the wetness of the spring on the
615 timing of planting, can modulated photosynthesis, and the temperature of the soil can affect ecosystem
616 respiration (Knox et al., 2016).

617 **Discussion and Synthesis**

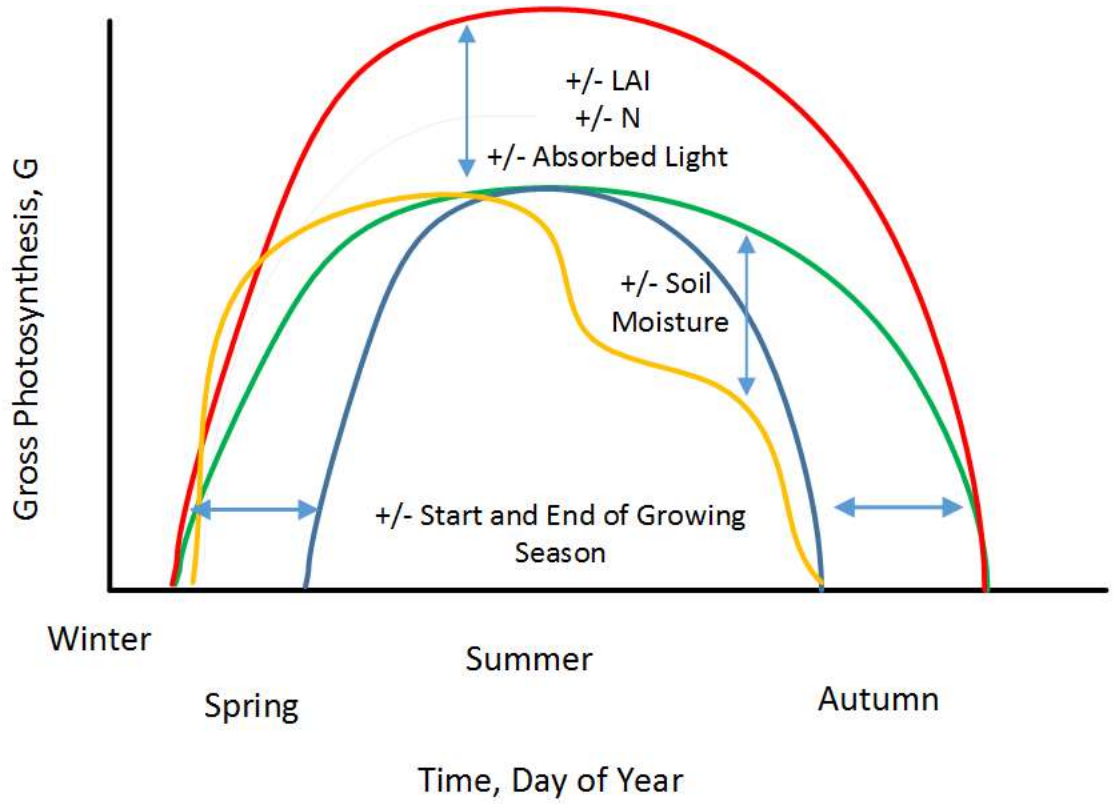
618 As we accumulate more and longer time series on net and gross carbon fluxes inquiries about the
619 relative contribution of climatic vs biotic drivers are being produced (Richardson et al., 2007; Shao et al.,
620 2015). The most exhaustive meta-analysis to date, using flux data from 65 sites, showed that biotic
621 factors contributed to 57% of the variability in net ecosystem exchange and climatic factors were
622 associated with the residual (43%) (Shao et al., 2015).

623 This literature review, performed on a larger body of data, reveals that a complex combination of
624 climate, ecological and disturbance variables can explain year to year variability in net and gross carbon
625 fluxes to different degrees in different parts of the world. Inspecting results from individual papers, we
626 have learned that variability in ecosystem photosynthesis is the more dominant factor causing
627 interannual variation in net ecosystem carbon exchange, N_E, for a complex combination of climatic and
628 ecological reasons.

629 In principle, there are a variety of factors that can modulate annual gross primary productivity from one
630 year to the next. Consider the conceptual figure where the green line is the baseline (Figure 9a).
631 Changes in the area under the curve can occur if the season starts earlier and/or ends later (blue line).
632 A growing number of studies are finding that that an earlier spring may positively modulate carbon
633 fluxes in a deciduous forest more, while later autumn has a greater impact on accumulated
634 photosynthesis of a boreal forest. Figure 9 also shows that there can be a bump in the midseason rate
635 of carbon uptake if more light is absorbed via more leaf area index, fewer clouds or higher
636 photosynthetic capacity and leaf nitrogen (red line). There can be a decrease in light absorption if there
637 is any legacy effect of dead biomass competing for photons the following year. The experience of a
638 summer drought will reduce carbon uptake later in the growing season, relative the baseline (yellow
639 line) (Reichstein et al., 2007; Wolf et al., 2016); this can occur by direct physiological stress and/or by a
640 co-occurring reduction in leaf area index.

641 The lower panel (figure 9b) shows related changes in ecosystem respiration, where the green line is the
642 baseline. Drought and reductions in photosynthesis (yellow line) reduce the time course in respiration.
643 Higher photosynthesis or photosynthetic capacity (red line) will have a compensatory increase in
644 ecosystem respiration. An earlier or later growing season (blue line) will promote respiration compared
645 to the base case.

646


+/- LAI
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Winter
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Summer
Autumn
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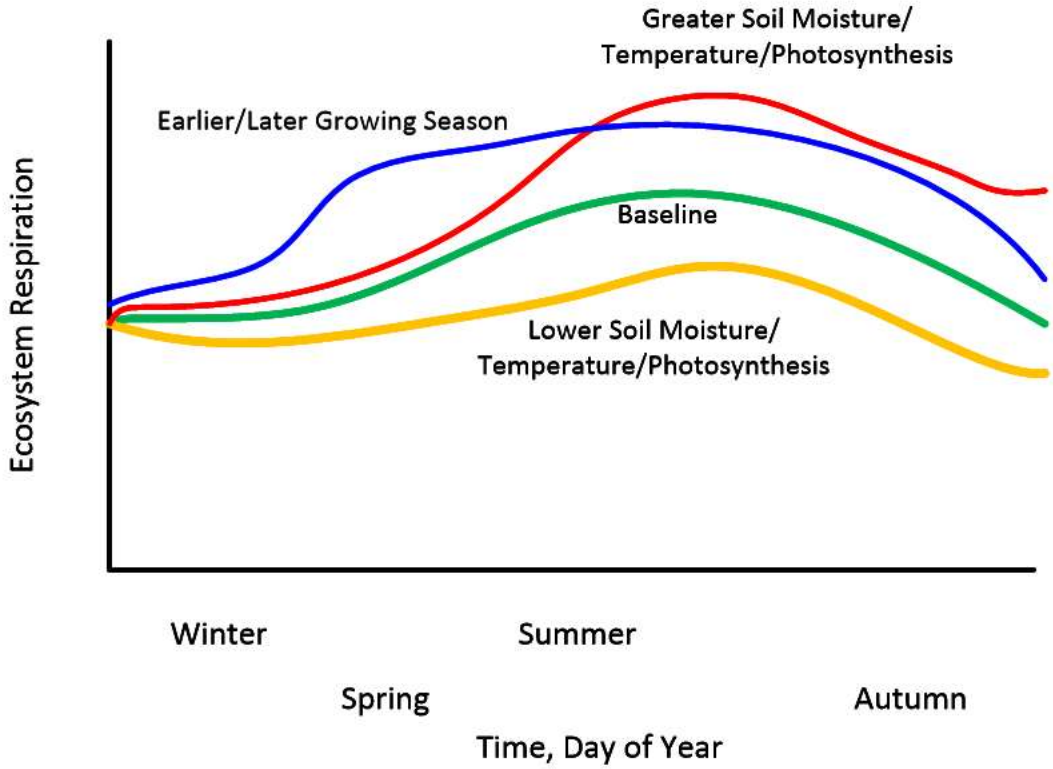
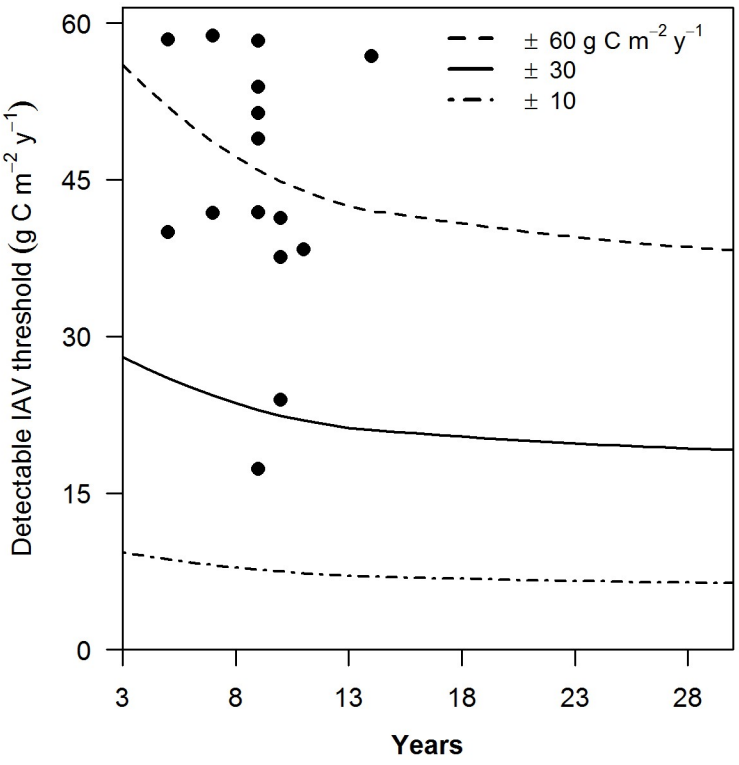

Greater Soil Moisture/ Temperature/Photosynthesis
Earlier/Later Growing Season
Baseline
Lower Soil Moisture/ Temperature/Photosynthesis
Ecosystem Respiration
Winter
Spring
Summer
Autumn
Time, Day of Year

647

Figure 9 Conceptual figure on how ecosystem photosynthesis, or gross primary production and ecosystem respiration may vary year to year by a set of biophysical forcings. The green line is the baseline. Yellow line is for a season with less soil moisture in late growing season. The blue line is for earlier start and later end of the growing season. The red line is for conditions that increase photosynthesis through more leaf area, more light absorption or greater photosynthetic potential though greater leaf nitrogen. The lower panel shows how ecosystem respiration may respond to these changes in photosynthesis and environmental conditions.

The standard deviations and trends of interannual variability, reported here, have uncertainties associated the intrinsic sampling and measurement error associated with the eddy covariance method and with the length of the time series. Using statistical sampling of random synthetic time series, we estimated the uncertainty of interannual carbon fluxes that one must exceed given the duration of the time series and the error of the measurements. We ran Monte Carlo simulations (N=5,000) to derive the detectable thresholds for trends and inter-annual variability of the annual carbon fluxes. The simulations begin with three levels of random uncertainties (i.e., +/-10, +/-30, to +/-60 g C m-1 y^{-1}, 95% CI) in the annual carbon fluxes. A series of artificial time series are then drawn from the proposed uncertainty distributions, and are used to calculate the trends (i.e., linear regression slope) and interannual variability (i.e., standard deviation). The 95% quantiles of the simulated trends and interannual variability are interpreted as the detectable thresholds. The simulations are carried out subsequently for time series ranging from 5 to 30 years.

Figure 10 shows that the threshold for detecting interannual variability in net carbon flux decreases as the duration of the time series increases and the sampling/measurement error decreases. For a conservative case, the interannual variability must exceed 50 gC m^{-2} y^{-1} to be attributed to non-random causes if the random sampling error was +/- 60 gC m^{-2} y^{-1} and the time series was 5 years long. This threshold drops to about 40 gC m^{-2} y^{-1} as the time series exceeds 20 years.



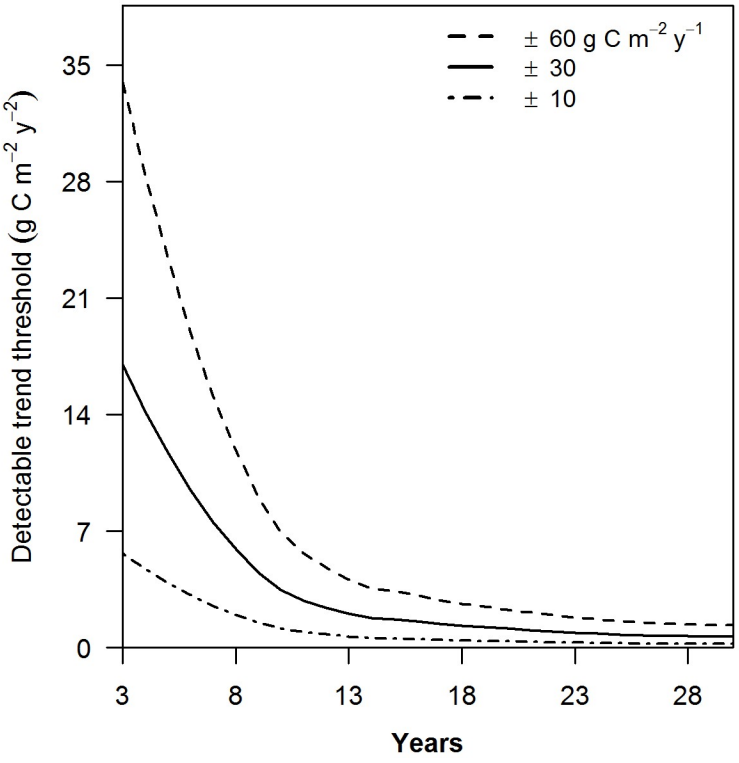
673

674 Figure 10 Confidence interval of standard deviation as a function of sample size and sampling error.
675 Superimposed on this figure are reported values (closed circles) from literature review. For better
676 presentation, only reported values lower than 60 gC m^{-2} y^{-1} were showed here.

677 The length of the time series has a marked impact on how well we can detect temporal trends, or not,
678 too (Shao et al., 2015). Figure 11 shows that that the 95% confidence interval of detectable trends
679 reduces markedly as the duration of the time series extends from 3 to 30 years. We find that
680 measured trends of interannual N_E must exceed 8 gC m^{-2} y^{-2} if the measurement error is 30 gC m^{-2} y^{-1} and
681 the time series is 5 years long for one to conclude that the noted variation is natural and not due to
682 randomness. If we have longer records, exceeding 20 years, we should be able to detect trends as small
683 as 3 gC m^{-2} y^{-2}.

684 Figure 11 gives us context with regards to interpreting reported trends if there is no systematic bias. For
685 example, Pilegaard et al (2011) reported a trend in their 13 year record equal to a slope of 25 gC m^{-2} y^{-2}
686 and Froelich et al. (2015) reported a trend of 15 gC m^{-2} y^{-2} from an 18 year record. Assuming a 30 gC m^{-2}
687 y^{-1} measurement/sampling error, these trends exceed the detectable limit due to random causes.

688



689

690 Figure 11 95% confidence intervals of trends in random time series of varying length and varying
691 measurement uncertainty.

692 *Closing comments*

693 We need long term carbon flux measurements for many reasons. Most importantly is to study
694 ecosystems on ecosystem time scales, which exceed decades. For example, long time series give us a
695 better and direct understanding how landscapes recover from disturbance, slow and steady process
696 (Odum, 1969). So far we have relied on chrono-sequences, time for space, to understand how net and
697 gross carbon exchange changes with time since disturbance (Amiro et al., 2010; Goulden et al., 2006).
698 But, this approach does not control for soil type and is often applied across large geographical areas.
699 Extending the time series of many disturbed forest sites beyond a decade and into multiple decades
700 remains an important goal for future long term research.

701 Secondly, long term flux studies are needed to provide information on whether or not, and if so, how
702 fast, ecosystem metabolism may be responding to a changing world that is warmer, bathed in more CO_2,
703 experiencing variation in rainfall and different degrees of nitrogen deposition, air pollution and
704 disturbance from humans, diseases and pests. This behavior, with co-occurring global warming, a
705 changing hydrological cycle and rising CO_2 will make even longer time series measurements crucial.
706 These datasets are invaluable and cannot be recreated if they are shut.

707 We also show clearly that longer time series are needed to distinguish trends from random noise and
708 that future evaluations of year to year variability should consider this possibility. Leaving on a positive
709 note, the uncertainty will decrease in a diminishing returns manner as the length of the time series
710 increase from 5 to about 20 years. Ideally, it will be a goal to produce a diverse number of carbon flux

time series reaching and exceeding 30 years. This will require long term investment by the funding agencies and an inter-generational transition in leadership of long term flux sites.

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1039

1040 Table 1 Table of literature surveyed

			NEE	NEE	GPP	GPP	Reco	Reco		
			gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}		
Country	Site	Functional Type	mean	std dev	mean	std dev	mean	std dev	n	author
Australia	Tumbarumba	Temperate, broadleaved evergreen forest	-584	333	NaN	NaN	NaN	NaN	11	(van Gorsel et al., 2013)
Austria	Stubai Valley	alpine meadow	-1	72	NaN	NaN	NaN	NaN	6	(Haslwanter et al., 2009)
Belgium	Brasschaat	Temperate, mixed deciduous broadleaved/conifer forest	-112	221	NaN	NaN	NaN	NaN	13	(Carrara et al., 2003; Gielen et al., 2013)
Brazil	Jaru	Tropical broadleaved, evergreen forest	-450	388	3413	333	2963	235	7	(Zeri et al., 2014)
Canada-British Columbia	Campbell River	Temperate, evergreen conifer forest	-356	51	2124	125	1768	146	9	(Chen et al., 2009a; Krishnan et al., 2009)
Canada-Manitoba	Thompson	Boreal, evergreen conifer forest	23	42	654	98	631	113	15	(Dunn et al., 2007; Soloway et al., 2017)
Canada-Ontario	Borden	Temperate, deciduous broadleaved forest	-177	116	1373	164	1196	188	18	(Froelich et al., 2015)
Canada-Quebec	Chibouugamau	Boreal, evergreen conifer forest	95	54	405	115	500	69	9	(Coursolle et al., 2012)
Canada-Saskatchewan	Prince Albert	Boreal, deciduous broadleaved forest	-168	96	1252	136	1084	103	9	(Barr et al., 2007)
China	Dinghushan	subtropical evergreen broadleaved forest	-393	104	1383	54	990	53	6	(Yan et al., 2013)
Denmark	Soroe	Temperate, deciduous broadleaved forest	-156	103	1727	136	1570	97	13	(Pilegaard et al., 2011)
Finland	Hyytiälä	Boreal, evergreen conifer forest	-206	38	1031	54	826	39	11	(Ilvesniemi et al., 2009)
Finland	Mekrijärvi	Boreal, evergreen conifer forest	-190	24	NaN	NaN	NaN	NaN	10	(Ge et al., 2011)
France	Hesse	Temperate, deciduous broadleaved forest	-386	171	1397	192	1011	137	10	(Granier et al., 2008)
France	Puechabon	evergreen oak woodland	-278	117	1317	151	1018	68	6	(Allard et al., 2008)
Germany	Hainich	Temperate, deciduous broadleaved forest	-483	70	1498	83	1015	51	7	(Herbst et al., 2015)
Germany	Tharandt	Temperate, evergreen conifer forest	-550	91	1845	162	1295	100	10	(Grunwald and Bernhofer, 2007)
Hungary	Hegihatsal	Temperate, grassland	-35	59	1096	180	1061	125	7	(Haszpra et al., 2005)

Ireland	Cork County, Ireland	Temperate, grassland	-164	150	1486	376	1343	247	8	(Jaksic et al., 2006)
Ireland	Glencar, County Kerry	Temperate, wetland	-56	17	288	18	232	8	9	(McVeigh et al., 2014)
Israel	Yatir	semi-arid evergreen conifer forest	-211	83	830	138	620	83	6	(Maseyk et al., 2008)
Japan	Fujiyoshida	Temperate, evergreen conifer forest	-388	58	1802	113	1413	97	9	(Mizoguchi et al., 2012)
Japan	Kiryu Watershed	Temperate, evergreen conifer forest	10	42	686	106	696	130	9	(Saigusa et al., 2005a)
Japan	Takayama	Temperate, deciduous broadleaved forest	-237	98	1110	409	829	264	9	(Kosugi et al., 2012)
Japan	Teshio Experimental Forest	Temperate, evergreen conifer forest	153	227	1013	315	1166	113	9	(Aguilos et al., 2014)
Mexico	LaPaz	desert scrub	92	113	NaN	NaN	NaN	NaN	7	(Bell et al., 2012)
Netherlands	Loobos	Temperate, evergreen conifer forest	-432	127	NaN	NaN	NaN	NaN	14	(Elbers et al., 2011)
Portugal	Espirra	Mediterranean, broadleaved evergreen forest	-472	319	1571	448	1099	148	8	(Rodrigues et al., 2011)
United Kingdom	Auchencorth Moss	Temperate, wetland	-64	38	737	168	674	165	10	(Helfter et al., 2011)
United Kingdom	Straights Inclosure	Temperature, deciduous broadleaved forest	-486	115	1993	275	1548	192	12	(Wilkinson et al., 2012)
US-Alaska	Alaska	Boreal, evergreen conifer forest	10	42	686	106	696	130	9	(Ueyama et al., 2014)
US-Alaska	Imnavait Creek Watershed	Wet sedge tundra	83	66	225	55	308	85	8	(Euskirchen et al., 2016)
US-Alaska	Imnavait Creek Watershed	Heath tundra	20	23	187	46	206	41	8	(Euskirchen et al., 2016)
US-Arizona	Flagstaff	Temperate, evergreen conifer forest	-104	99	952	97	866	44	5	(Scott et al., 2014)
US-Arizona	Flagstaff	Temperate, evergreen conifer forest	-113	70	935	94	844	79	5	(Dore et al., 2012)
US-Arizona	San Pedro	semi-arid woodland	-309	110	979	185	670	135	15	(Dore et al., 2012)
US-California	Ione	Mediterranean, savanna/grassland	-110	57	1056	145	946	141	14	(Ma et al., 2016)
US-California	Twitchell Island	rice	-34	237	1437	140	1414	223	6	(Ma et al., 2016)
US-California	Ione	Mediterranean, grassland	7	113	682	169	689	126	15	(Knox et al., 2016)
US-Florida	Gainsville, Donaldson Tract	Sub-tropical, evergreen conifer forest	-669	99	2490	144	1821	156	10	(Bracho et al., 2012)

US-Florida	Gainsville, Mize Tract	Sub-tropical, evergreen conifer forest	112	683	2200	794	2312	245	11	Bracho et al. 2012)
US-Indiana	Morgan-Monroe	Temperature, deciduous broadleaved forest	-351	81	1452	118	1098	82	13	(Sulman et al., 2016)
US-Iowa	Ames	Prairie	-105	80	919	99	813	79	9	(Dold et al., 2017)
US-Iowa	Ames	Corn	-128	211	1016	383	888	194	10	(Dold et al., 2017)
US-Iowa	Ames	Corn	-137	241	927	358	789	130	10	(Dold et al., 2017)
US-Maine	Howland	boreal, evergreen conifer forest	-188	49	1343	95	1168	80	9	(Hollinger et al., 2004)
US-Massachusetts	Harvard Forest, Petersham	temperate, deciduous broadleaved forest	-245	100	1400	164	1153	105	13	(Urbanski et al., 2007)
US-Michigan	Douglas Lake	mixed deciduous forest	-151	40	NaN	NaN	NaN	NaN	5	(Curtis et al., 2005)
US-Missouri	Ozarks	temperate, deciduous broadleaved forest	-479	65	1125	164	646	121	5	(Shao et al., 2014)
US-Nebraska	Mead	irrigated crops	-253	334	1384	447	1131	125	8	(Suyker and Verma, 2012)
US-Nebraska	Mead	rainfed crops	-225	268	1201	347	976	102	8	(Suyker and Verma, 2012)
US-New Mexico	Sevilleta LTER	desert grassland	28	63	155	72	183	39	5	(Petrie et al., 2015)
US-North Carolina	Duke Forest, Durham	grassland	218	58	1648	371	1868	422	5	(Novick et al., 2015)
US-North Carolina	Duke Forest, Durham	temperate, deciduous broadleaved forest	-402	96	1982	300	1580	237	8	(Novick et al., 2015)
US-North Carolina	Duke Forest, Durham	temperate, evergreen conifer forest	-503	176	2343	319	1848	179	8	(Stoy et al., 2008)
US-Oregon	Metolius	temperate, evergreen conifer forest	-465	116	1583	173	1118	89	7	(Thomas et al., 2013)
US-Tennessee	Oak Ridge	temperate, deciduous broadleaved forest	-577	63	NaN	NaN	NaN	NaN	5	(Wilson and Baldocchi, 2001)
US-Washington	Wind River	temperate, evergreen conifer forest	-32	85	1382	92	1350	145	16	(Wharton and Falk, 2016)
US-Wisconsin	Park Falls	mixed deciduous forest	123	42	NaN	NaN	NaN	NaN	7	(Ricciuto et al., 2008)

Table

			NEE	NEE	GPP	GPP	Reco	Reco		
			gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}	gC m^{-2} y^{-1}		
Country	Site	Functional Type	mean	std dev	mean	std dev	mean	std dev	n	author
Australia	Tumbarumba	Temperate, broadleaved evergreen forest	-584	333	NaN	NaN	NaN	NaN	11	(van Gorsel et al. 2013)
Austria	Stubai Valley	alpine meadow	-1	72	NaN	NaN	NaN	NaN	6	(Haslwanter et al. 2009)
Belgium	Brasschaat	Temperate, mixed deciduous broadleaved/conifer forest	-112	221	NaN	NaN	NaN	NaN	13	(Carrara et al. 2003; Gielen et al. 2013)
Brazil	Jaru	Tropical broadleaved, evergreen forest	-450	388	3413	333	2963	235	7	(Zeri et al. 2014)
Canada-British Columbia	Campbell River	Temperate, evergreen conifer forest	-356	51	2124	125	1768	146	9	(Chen et al. 2009; Krishnan et al. 2009)
Canada-Manitoba	Thompson	Boreal, evergreen conifer forest	2	41	706	57	713	79	10	(Dunn et al. 2007)
Canada-Ontario	Borden	Temperate, deciduous broadleaved forest	-177	116	1373	164	1196	188	18	(Froelich et al. 2015)
Canada-Quebec	Chibouugamau	Boreal, evergreen conifer forest	95	54	405	115	500	69	9	(Coursolle et al. 2012)
Canada-Saskatchewan	Prince Albert	Boreal, deciduous broadleaved forest	-168	96	1252	136	1084	103	9	(Barr et al. 2007)
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US-Missouri	Ozarks	temperate, deciduous broadleaved forest	-479	65	1125	164	646	121	5	(Shao et al. 2014)
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US-Washington	Wind River	temperate, evergreen conifer forest	-32	85	1382	92	1350	145	16	(Wharton; Falk 2016)
US-Wisconsin	Park Falls	mixed deciduous forest	123	42	NaN	NaN	NaN	NaN	7	(Ricciuto et al. 2008)

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List of Figures

Figure 9.

Conceptual figure on how ecosystem photosynthesis, or gross primary production and ecosystem respiration may vary year to year by different biophysical forcings. The green line is the baseline. Yellow line is for a season with less soil moisture in late growing season. The blue line is for earlier start and later end of the growing season. The red line is for conditions that increase photosynthesis through more leaf area, more light absorption or greater photosynthetic potential though greater leaf nitrogen. The lower panel shows how ecosystem respiration may respond to these changes in photosynthesis and environmental conditions.

Figure 10.

Confidence interval of standard deviation as a function of sample size and sampling error. Superimposed on this figure are reported values (closed circles) from literature review. For better presentation, only reported values lower than 60 gC m^{-2} y^{-1} were showed here.

Figure 11.

95% confidence intervals of trends in random time series of varying length and varying measurement uncertainty.

Figure 1

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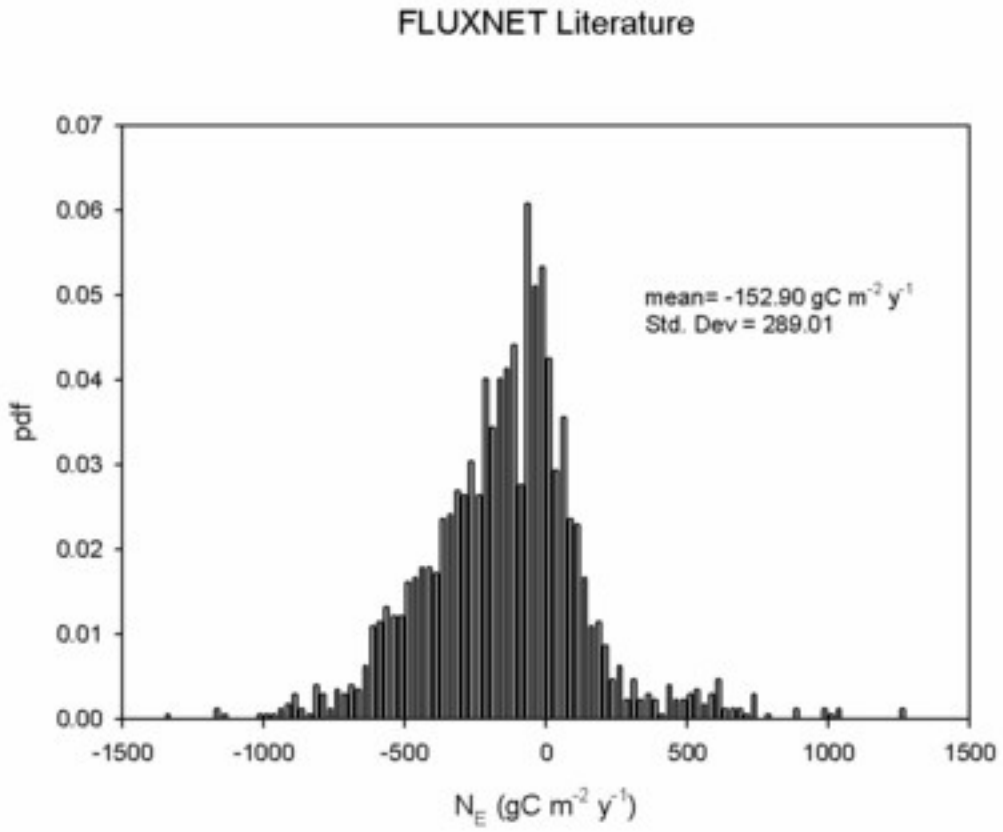

Figure 2
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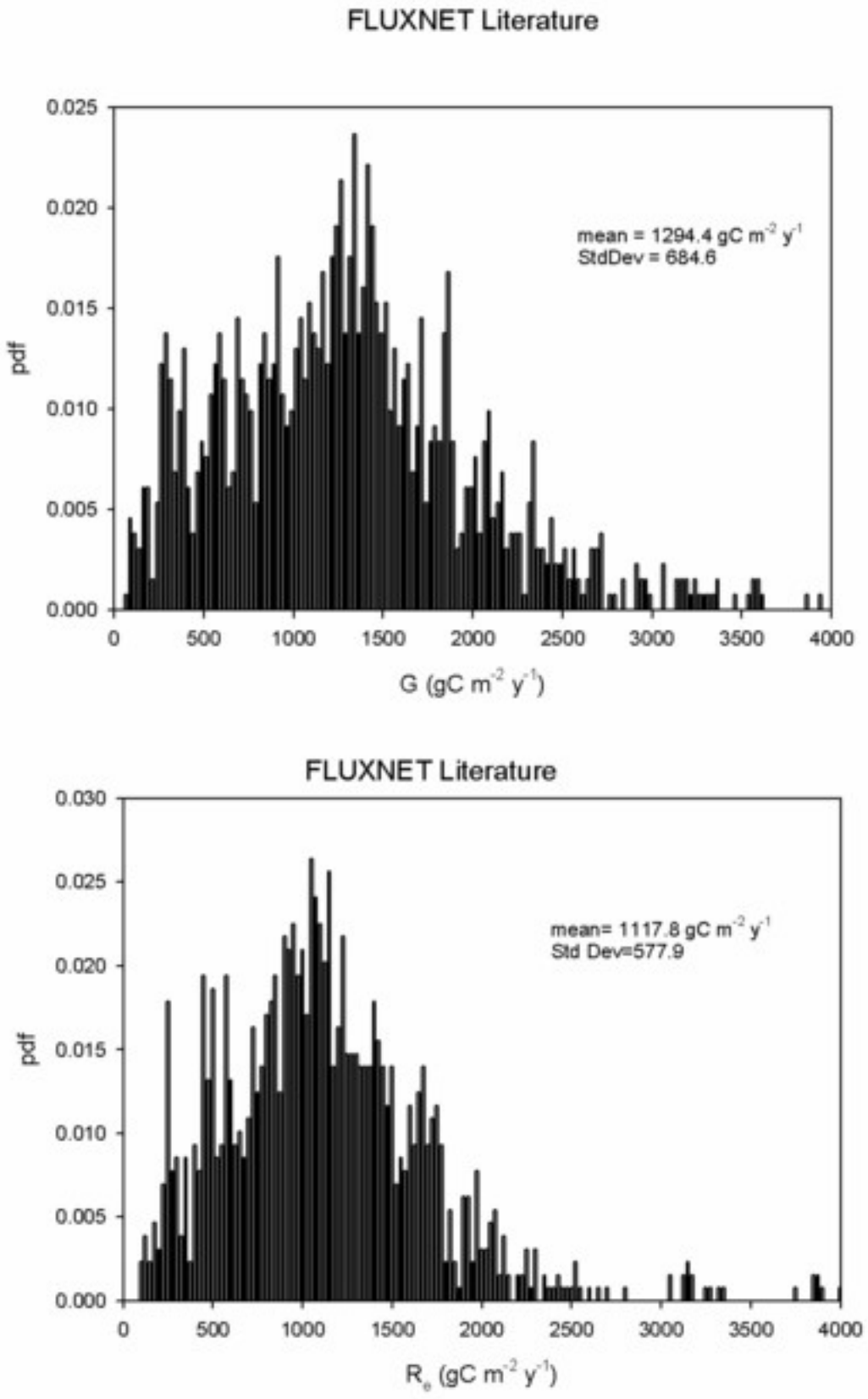

Figure 3

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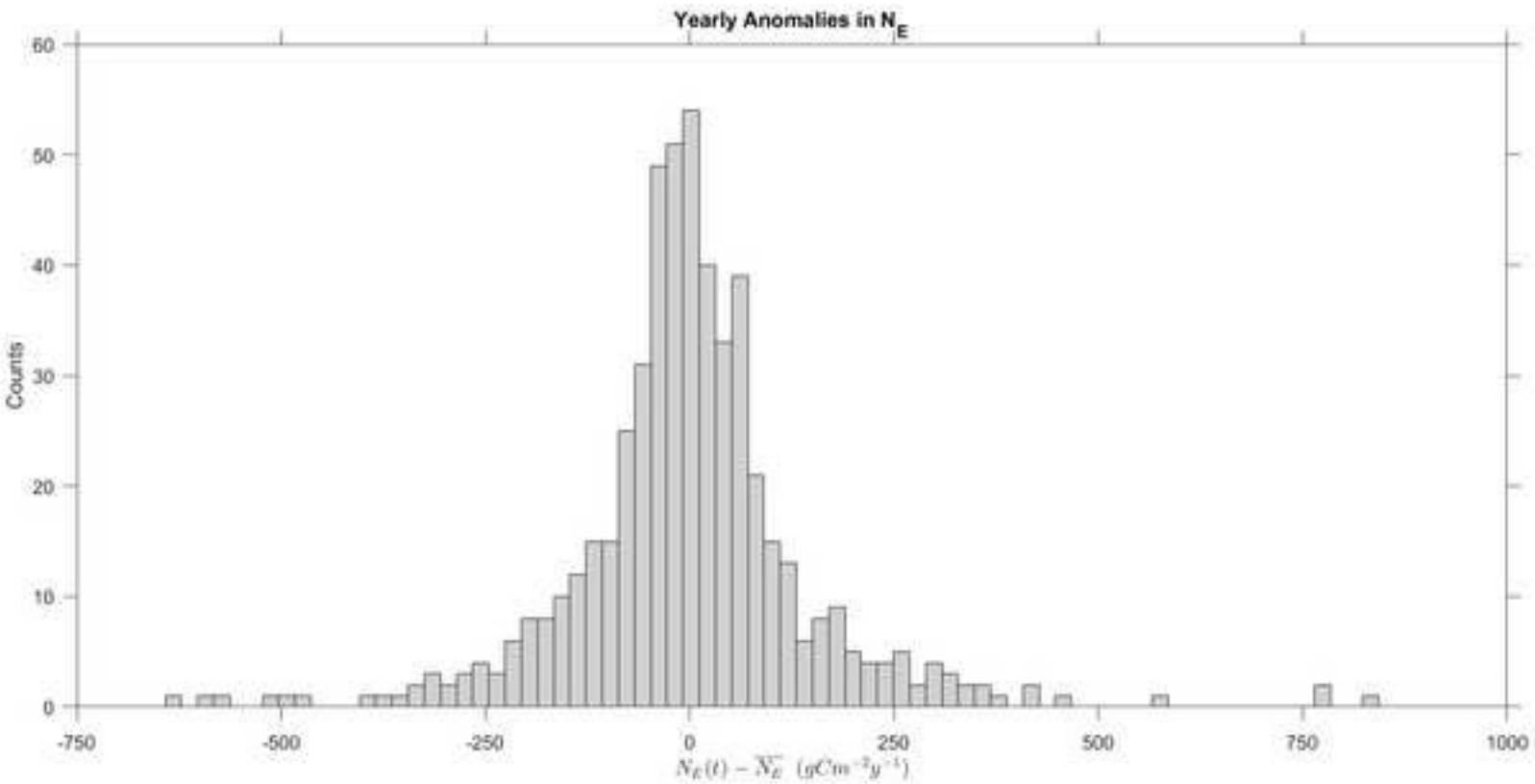

Figure 4ab

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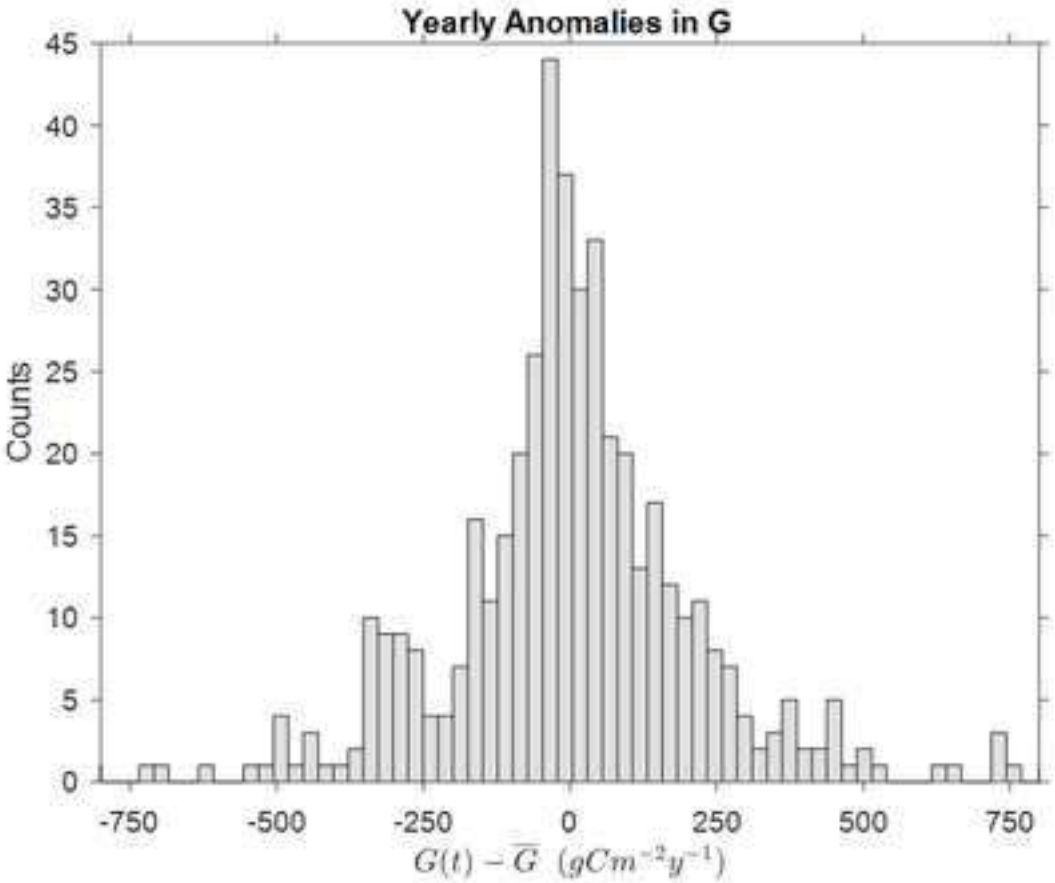

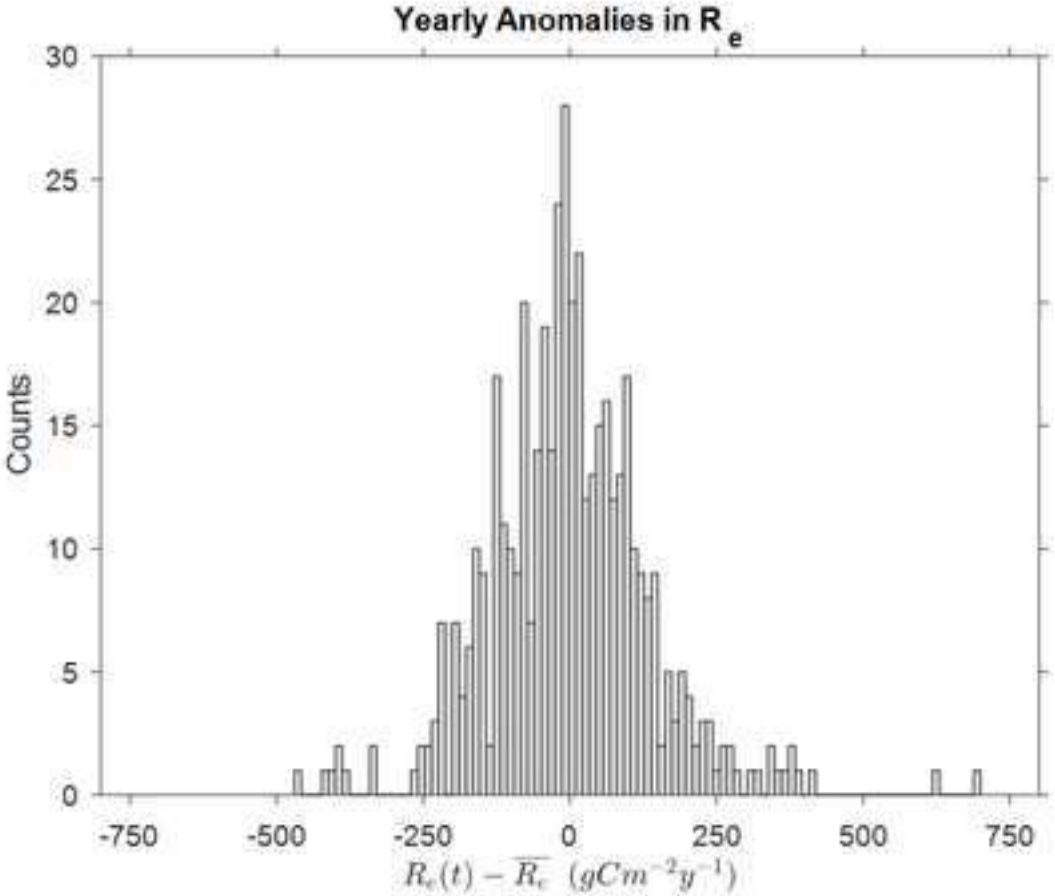

Figure 5

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